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LATE PROTEROZOIC TECTONIC MODEL FOR THE AVALON TERRANE IN MARITIME CANADA

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Abstract. The Avalon Terrane in Maritime Canada extends from Cape Breton Island through northern Nova Scotia (Antigonish and Cobequid highlands) to southern New Brunswick. The terrane contains abundant late Proterozoic volcanic rocks (~570-680 m.y. old). The geochemistry of the volcanic rocks of southern Cape Breton Island and southern New Brunswick indicates that they were erupted in a volcanic arc environment. In both regions the mafic rocks display a remarkably similar compositional zonation which resembles the across-arc variations observed in modern volcanic arcs. The progressive compositional changes that include a transition from island arc tholeiites along the southeastern coasts to calc-alkaline rocks inland to the northwest are probably due to a northwest dipping subduction zone with a trench located to the southeast. In the Antigonish and Cobequid highlands, continental tholeiites and calc-alkaline volcanic rocks are interbedded and overlain by turbidites that have probably been deposited in a back arc or intra-arc environment. The superimposed positive gravity and magnetic anomalies that may be traced discontinuously from the Grand Banks through Nova Scotia (Collector Anomaly) and along the northern side of the Gulf of Maine to near Boston, probably represent late Proterozoic ophiolitic remnants preserved by incomplete suturing along a late Proterozoic plate boundary. Northeast trending segments are inferred to mark subduction zones, and the E-W portions could correspond to transform faults. Thus the present geographical distribution of the Late Proterozoic volcanic rocks is explained by a tectonic model involving a single subduction zone offset by two late Proterozoic transform faults located approximately along the Minas Fault and the Scatarie Ridge.

INTRODUCTION

The Avalon Terrane or Zone [Williams, 1978; Keppie, 1989 and references therein] of the northern Appalachians is a composite terrane containing abundant late Proterozoic volcanic rocks that extends along the eastern seaboard of North America from eastern Newfoundland through northern Nova Scotia, southern New Brunswick, and Maine to southeastern New England. The terrane is characterized by a lower Paleozoic overstep sequence composed of platformal sediments with Acado-Baltic and Rhenish-Bohemian faunas. This sequence overlies a variety of Precambrian rocks units: belts of variably metamorphosed late Proterozoic igneous rocks and turbiditic sediments and middle/late Proterozoic metamorphic rocks. Differences in the late Proterozoic stratigraphy led to the subdivision of the Avalon Zone into several terranes [Keppie, 1985; Barr and Raeside, 1989]; however, lithostratigraphic correlations across northern Nova Scotia and southern New Brunswick suggest that this region represents part of one late Proterozoic terrane [Keppie, 1989, 1990]. Despite these differences in interpretation, all workers agree that areas underlain [illegible]e late Proterozoic volcanic rocks of the [illegible]rook and Fourchu groups are part of the [illegible]ion Terrane.

Recent geochemical and geochronological data on the late Proterozoic volcanic rocks from Nova Scotia and New Brunswick put constraints on the evolution of this part of the Avalon Terrane. The purpose of this paper is to summarize and compare the data on approximately coeval late Proterozoic volcanic rocks from four areas (southeastern Cape Breton Island, the Antigonish and Cobequid highlands in northern Nova Scotia, and the Caledonian Highlands in southeastern New Brunswick) and to propose an integrated tectonic model for the Canadian Maritime part of the Avalon Terrane during the late Proterozoic. The model is evaluated using geophysical data for the region.

GEOLOGICAL SETTING

In the Avalon Terrane of Maritime Canada the oldest exposed rocks are gneisses and amphibolites with ages ranging between about 560 and 1050 Ma [Barr et al., 1987; Doig et al., 1989; Bevier et al., 1990]. Generally in tectonic contact with these gneissses is a lithostratigraphic unit composed of platformal metasedimentary rocks (quartzites, sandstones, and carbonates) possibly of middle-late Proterozoic (middle Rhipean) age [Hoffmann, 1974]. These units are inferred to underlie the late Proterozoic sequences that consist predominantly of volcanic rocks about 570-680 m.y. old. These late Proterozoic rocks crop out in southeastern Cape Breton Island (Fourchu Group), in the Antigonish Highlands (Georgeville Group), in the Cobequid Highlands (Folly River and the Jeffers groups), and in southeastern New Brunswick (Coldbrook Group) (Figure 1).

The Fourchu Group occurs in several NE trending fault blocks in southeastern Cape Breton Island, which are (from southeast to northwest) Coastal, Stirling, East Bay Hills, and Coxheath blocks. The volcanic sequences are composed predominantly of subaerial-shallow marine pyroclastic rocks, flows, and small intrusive bodies.

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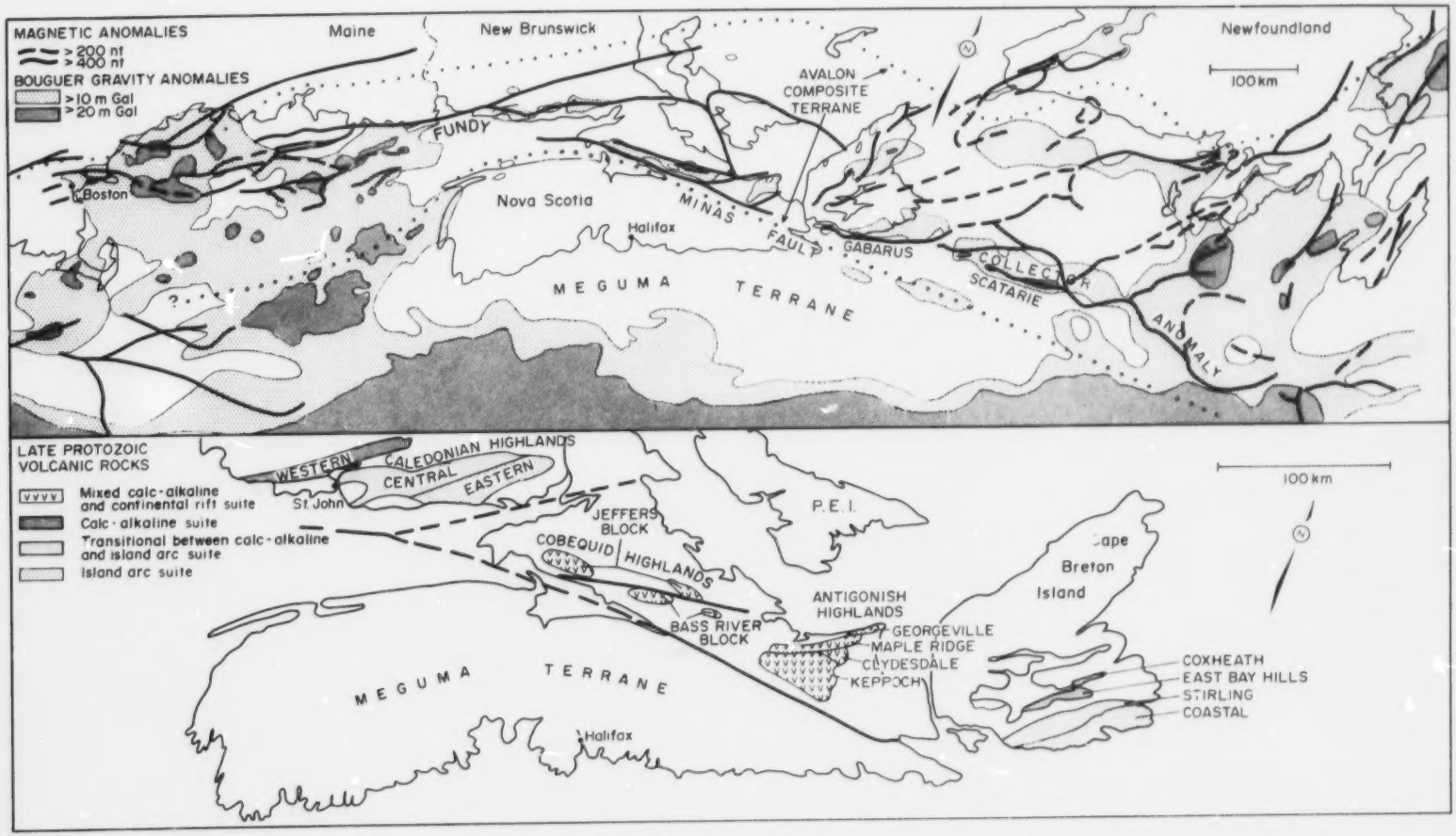

Fig. 1. Map of the coastal region of New England and Atlantic Canada showing the late Proterozoic volcanic rocks discussed in the text and the axes of gravity and magnetic anomalies [after Williams and Haworth, 1984a, b; Loncarevic et al., 1989; Pe-Piper and Loncarevic, 1989]. Dotted lines delimit the Avalon Composite Terrane.

The suites include mafic and felsic types with subordinate units of intermediate composition. The Stirling block is distinctive due to the presence of a massive sulphide deposit, turbiditic sedimentary rocks, and chemical sediments (cherts and carbonates). The volcanic rocks of the Fourchu Group have yielded concordant U-Pb zircon ages of (1) 574 ± 1 Ma in the Coastal block; (2) 676 ± 1 Ma in the Stirling block; and (3) about 600-660 Ma in the East Bay Hills block [Barr et al., 1990a]. The Coxheath volcanic rocks were inferred to be synchronous with crosscutting plutonic rocks that have yielded $^{40}Ar/^{39}Ar$ hornblende plateau ages between 600 and 635 Ma [Keppie et al., 1990]. Plutons 600-635 m.y. old are also present in the East Bay Hills and Stirling blocks [Keppie et al., 1990; Barr et al., 1990b]. The U-Pb ages represent one datum in a thick pile of volcanic rocks in each fault block, and the time span represented by the volcanism appears to have lasted at least 100 m.y.

The late Proterozoic Georgeville Group of the Antigonish Highlands is subdivided into several east or northeast trending fault blocks which are (from south to north) Keppock, Clydesdale, Maple Ridge, and Georgeville blocks [Murphy and Keppie, 1987]. The Keppock block consists of >3000 m of interlayered felsic volcanic rocks, basalts, and porphyritic basaltic andesites overlain by turbidites. The Clydesdale block contains turbidites with thin interlayered mafic volcanic rocks. The Maple Ridge block is made up entirely of a thick turbidite sequence. In the Georgeville block, interlayered basaltic andesites and marbles are overlain by turbidites and conglomerates that yielded detrital grains of zircons with the youngest U-Pb ages ranging between 605 and 625 Ma [Keppie and Krogh, 1990]. The late Proterozoic strata were then deformed and intruded by mafic plutons with $^{40}Ar/^{39}Ar$ hornblende plateau ages between 600 and 625 Ma [Keppie et al., 1990]. In these blocks, deposition, deformation, volcanism, and plutonism took place over just a few million years.

Late Proterozoic rocks in the Cobequid Highlands occur mainly in two isolated fault blocks, Bass River and Jeffers blocks (from south to north) [Murphy et al., 1988; Pe-Piper and Piper, 1989]. They are lithologically comparable to the units in the Antigonish Highlands. As in the Antigonish Highlands, these late Precambrian rocks were deformed shortly before being intruded by plutons yielding ages about 600-625 Ma [Gaudette et al., 1984; Donohoe et al., 1986; Keppie et al., 1990].

The Coldbrook Group in southern New Brunswick is composed of volcanic rocks with minor intercalated sedimentary rocks. It is exposed in three northeast trending belts (Eastern, Central, and Western) which are separated by intrusive rocks [Ruitenberg et al., 1979]. The Eastern belt is made up of two contrasting volcanic sequences [McLeod, 1986, 1987; Barr and White, 1988]. One largely subaerial sequence (A) is of Eocambrian age (ca. 550 Ma [Bevier and Barr, 1990] and is excluded from the tectonic model in this paper. The other sequence (B) is inferred to unconformably underlie the Eocambrian sequence and has U-Pb zircon ages of 600-635 Ma [Bevier and Barr, 1990]. This older sequence consists of massive and pillowed basaltic lavas, pillow breccias, tuffs, and sediments. The Central volcanic belt is composed predominantly of bimodal, terrestrial strata, at least 8 km thick [Ruitenberg et al., 1979]. The most abundant types are felsic tuffs and flows. The Western belt comprises largely terrestrial felsic volcanic rocks in the southern part and a bimodal volcanic suite including both lavas and pyroclastic types in the northern section [McCutcheon and Ruitenberg, 1987]. The age of the volcanic rocks in the Central and Western belts is probably in the range of 600-640 Ma [Stukas, 1978; Watters, 1987; Barr, 1987; McLeod, 1987; Barr and White, 1988]. All of these late Proterozoic volcanic rocks from Maritime Canada were metamorphosed, probably during the Devonian, under greenschist to sub-greenshist facies conditions.

GEOCHEMISTRY

Southern Cape Breton Island

The late Proterozoic volcanic rocks of the Fourchu Group are predominantly bimodal, although in the Coxheath and East Bay Hills blocks the intermediate types are abundant. In these two blocks, mafic rocks are also, on average, higher in SiO_2. The geochemistry of the mafic rocks from the four fault blocks is characteristic of lavas from orogenic zones [Dostal et al.,1990] (Figure 2). The basaltic rocks of the Coastal block are tholeiitic, whereas the mafic lavas of the East Bay Hills and Coxheath blocks are calc-alkaline and those of the Stirling block are intermediate between these two types. The basalts of the Coastal block have the lowest abundances of incompatible elements including high-field-strength elements (HFSE) and large ion lithophile elements (LILE) and resemble island arc tholeiites. The abundances of these incompatible elements progressively increase from the Coastal block through basalts of the Stirling and East Bay Hills to the Coxheath calc-alkaline basalts (Figures 3 and 4). The Stirling metabasalts have abundances of highly and moderately incompatible trace elements overlapping those of calc-alkaline basalts and tholeiites from evolved island arcs. The abundances of these elements in East Bay Hills and Coxheath mafic rocks are notably higher and are similar to calc-alkaline basalts emplaced on continental margins. Assuming that these four volcanic suites are related to the same subduction zone, the progressive compositional changes in the Fourchu mafic rocks across southeastern Cape Breton Island are similar to trends observed in modern island arcs [Gill, 1981] and are probably due to a northwest dipping subduction zone with a trench located southeast of the Coastal block [Dostal et al., 1990].

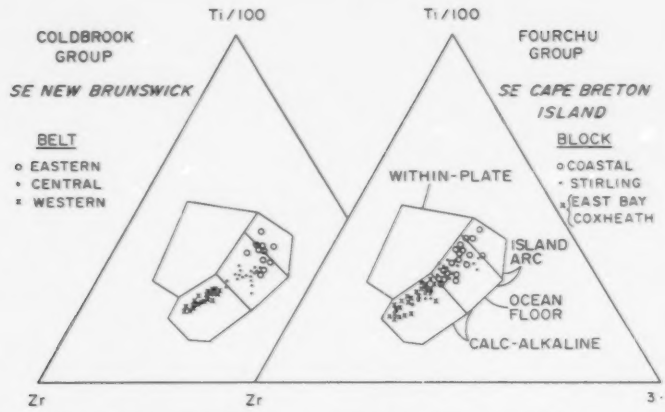

Fig. 2. Ti-Zr-Y diagrams of Pearce and Cann [1973] for basaltic rocks of the Coldbrook and Fourchu groups.

Antigonish and Cobequid Highlands

The late Proterozoic volcanic rocks in the Antigonish and Cobequid highlands have been studied by Murphy et al. [1990] and Pe-Piper and Piper [1989], respectively. In both areas the rocks consist of two groups which, in places, are intercalated. These two groups have also been recognized in the associated minor hypabyssal intrusions which appear to be comagmatic with the basalts. The first group has a bimodal distribution of mafic and voluminous felsic types; the mafic rocks are aphyric continental tholeiites (Figures 5 and 6) high in Fe and Ti. The second group includes a suite of rocks ranging from basalts or basaltic andesites to rhyodacites. The mafic rocks of the second group are porphyritic and have compositional characteristics of subduction-related calc-alkaline types (Figures 5 and 6). The close association of these two groups of volcanic rocks suggests that they were extruded in an intra-arc/back arc basin.

Southern New Brunswick

The mafic volcanic rocks of the Coldbrook Group [Dostal and McCutcheon, 1990] resemble those of recent orogenic sequences (Figure 2) and bear compositional similarities to those of the

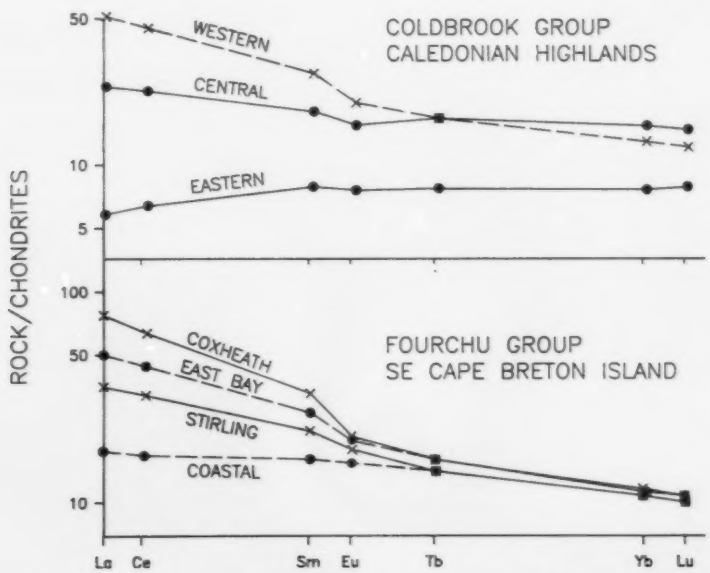

Fig. 3. Chondrite-normalized rare earth element composition of the averages of the basaltic rocks from the Coldbrook and Fourchu groups. Data are from Dostal et al. [1990] and Dostal and McCutcheon [1990]. Normalizing values after Frey et al. [1968].

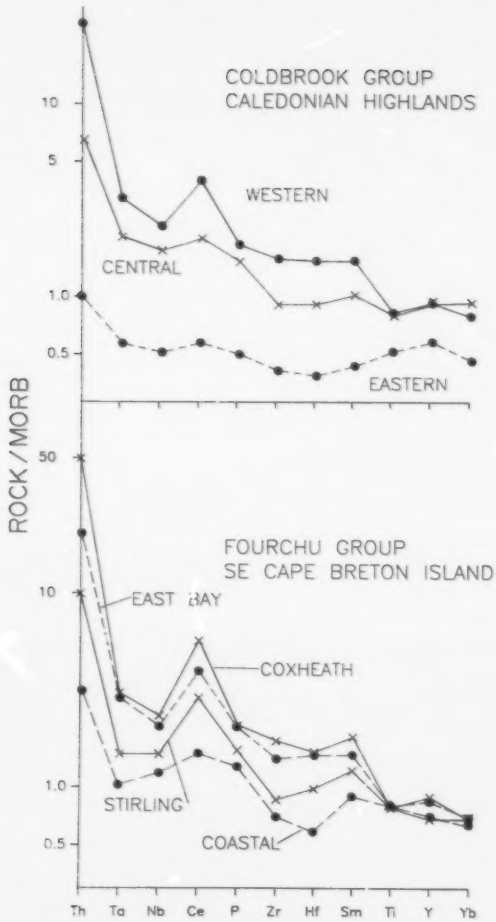

Fig. 4. Plots of incompatible element abundances normalized to primitive mantle [Sun and McDonough, 1989] for the averages of the basaltic rocks from the Coldbrook and Fourchu groups. Data from Dostal et al. [1990] and Dostal and McCutcheon [1990].

Fourchu Group. The late Proterozoic mafic rocks are mainly basalts: tholeiitic in the Eastern and calc-alkaline in the Western block. The Central belt basalts are intermediate between the other two types. The Eastern belt tholeiites are depleted in incompatible elements including HFSE and light rare earth elements (LREE) (Figures 3 and 4) and resemble island arc tholeiites. The basalts from the Central block are also tholeiites, but their abundances of incompatible elements (Figures 3 and 4) are enriched compared to those of the Eastern block and display some similarities to those of calc-alkaline basalts of island arcs. These characteristics together with the relative abundances of felsic rocks including ignimbrites and the presence of shallow subaqueous and subaerial sedimentary rocks [Ruitenberg et al., 1979] suggest that the mafic rocks of the Central block were emplaced in an volcanic

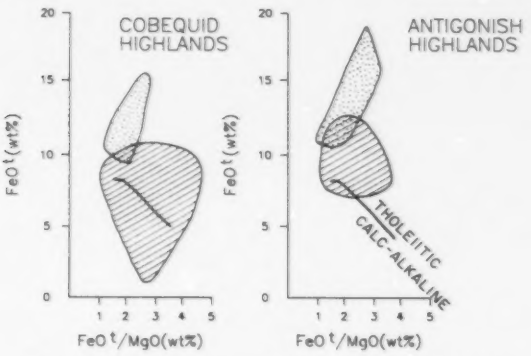

Fig. 5. FeO^t/MgO versus FeO^t diagram for the late Proterozoic rocks of the Cobequid and Antigonish highlands. Modified from Murphy et al. [1990] and Pe-Piper and Piper [1989]. Dividing line between calc-alkaline and tholeiitic rocks after Miyashiro [1974]. Calc-alkaline suites, striped areas; tholeiitic rocks, dotted areas.

arc setting on a continental crust [Dostal and McCutcheon, 1990]. The mafic rocks of the Western belt are typical calc-alkaline basalts and basaltic andesites. They have the highest contents of incompatible elements and the largest enrichment of LILE which, together with abundant associated felsic volcanic rocks, are consistent with an emplacement in a continental margin setting.

TECTONIC IMPLICATIONS

The mafic rocks of the volcanic suites of the Coldbrook and Fourchu groups show remarkable similarities in compositional zonation, ranging from island arc tholeiites along the southestern coast to calc-alkaline basalts inland to the northwest. This zonation is comparable to the across-arc variations observed in modern volcanic arc systems. Assuming that the blocks were not tectonically shuffled, the geochemical characteristics indicate that in late Proterozoic time the trench was located southeast of the coasts of Cape Breton Island and southern New Brunswick with a northwesterly dipping subduction zone. The Fourchu and Coldbrook groups are both in fault contact on their northwestern side with middle/late Proterozoic gneisses and miogeoclinal metasedimentary rocks (Green Head and George River groups), which are inferred to underlie the late Proterozoic volcanic rocks. In modern forearcs, island arc tholeiites are commonly associated with metamorphic and ophiolitic rocks and are flanked by a flysch belt adjacent to the trench. The occurrences of such associated late Proterozoic metamorphic, ophiolitic, and flyschoid rocks have not yet been documented, but they could lie some distance offshore and not be presently exposed. The geochemical signatures of the late Proterozoic continental tholeiites and calc-alkaline volcanic rocks of the Antigonish and Cobequid highlands are

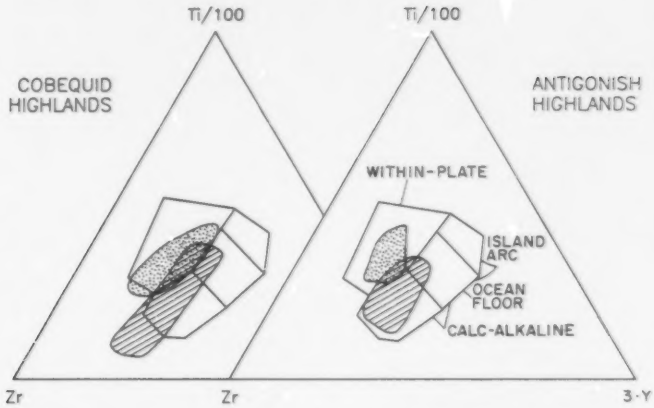

Fig. 6. The diagrams of Ti-Zr-Y of Pearce and Cann [1973] for the late Proterozoic mafic rocks of the Cobequid and Antigonish highlands. Calc-alkaline suites, striped areas; tholeiitic rocks = dotted areas.

consistent with either a back arc or intra-arc rift tectonic setting.

Three tectonic models may be applied to the present geographical distribution of the late Proterozoic rocks in Nova Scotia and southern New Brunswick based upon the tectonic settings deduced from the stratigraphy and geochemistry of the rocks (Figure 7):

Model 1. During the late Proterozoic there were two northwest dipping subduction zones, one beneath Cape Breton Island and the second beneath southern New Brunswick.

Model 2. During the late Proterozoic, southern New Brunswick and southern Cape Breton Island were laterally continuous and there was just one northwest dipping subduction zone, which, during the Paleozoic, was offset dextrally along the Minas Fault and then along the Chignecto Fault (Figure 7). This model was originally invoked by Keppie [1982]. However, Keppie and Dallmeyer [1987] subsequently proposed that the Meguma Terrane is thrust upon the Avalon Terrane with the Minas Fault acting as a lateral ramp. In the latter case, units in Cape Breton Island may be merely depressed beneath the Meguma allochthon. Alternatively, the Avalon Terrane may be displaced by sub-Meguma thrust faults, in which case the amount of displacement could range up to 370 km, which is the inferred displacement of the western margin of the Meguma Terrane [Keppie, 1982].

Model 3. During the late Proterozoic there was one northwest dipping subduction zone offset by two transform faults located along E-W trending segments (Minas Fault and Scatarie Ridge). A very similar, modern analogue of a subduction zone offset by two transform faults occurs in the Cayman Trough-Puerto Rico Trench-Barbados Trench system [Howell et al., 1985].

These three models may be evaluated using geophysical data, because any ophiolitic remnants predicted by the tectonic models should be reflected by superimposed large positive magnetic and gravity anomalies. The only major superimposed gravity and magnetic anomaly in the region is the Collector Anomaly (Figure 1) [Williams and Haworth, 1984a, b; Lefort, 1989]. This anomaly was originally defined as the superimposed positive gravity and magnetic anomalies along the Scatarie Ridge, east of Cape Breton Island [Haworth, 1975], and derives its name from the way that all the magnetic anomalies extending south from Newfoundland collect along the Collector Anomaly. Haworth and MacIntyre [1975] interpreted the sigmoidal shape of the merging anomalies in terms of dextral fault displacement along the Collector Anomaly. However, this fault was terminated just off Cape Breton Island. Subsequently, Lefort [1989] extended the Collector Anomaly through Nova Scotia and along the Gulf of Maine into New England north of Boston based upon a correlation of large and distinctive superimposed positive gravity and magnetic anomalies. However, it is clear that the Collector Anomaly is segmented, so the various segments have been named here as follows: Scatarie, Gabarus, Minas, and Fundy (Figures 1 and 7). A spur of the Collector Anomaly runs part of the way up Chignecto Bay, but the positive gravity anomaly dies out south of the isthmus between New Brunswick and Nova Scotia even though the positive magnetic anomaly continues to Prince Edward Island. The Collector Anomaly has been interpreted in terms of high-density, highly magnetic mafic-ultramafic rocks [Lefort, 1989]. Using a layer-stripping method, Pe-Piper and Loncarevic [1989] have shown that the source of the positive magnetic anomaly lies at a depth of 4-8 km along the Fundy and Minas segments. The surface location of the superimposed positive gravity and magnetic anomalies will be dependent upon the dip of these mafic-ultramafic rocks and will only coincide with surface features if they are vertical bodies. Along the Minas segment and the northeastern end of the

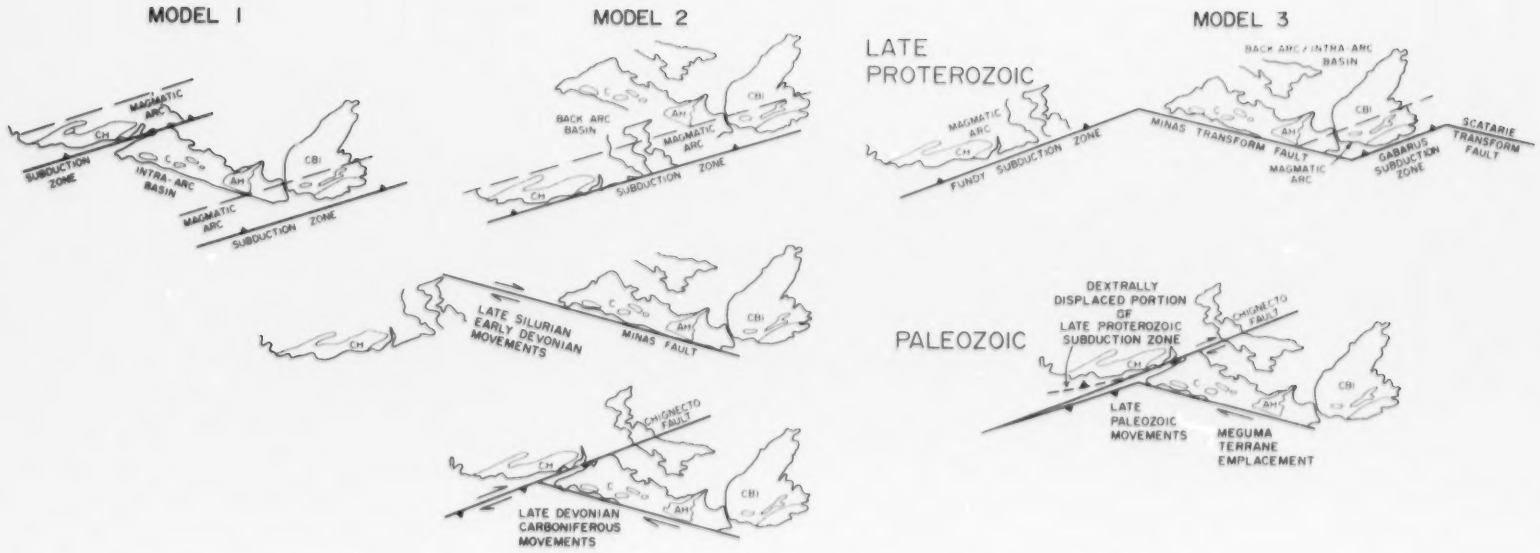

Fig. 7. Three possible tectonic models to explain the present distribution of late Proterozoic volcanic rocks in the Avalon Terrane of Maritime Canada. CH, Caledonian Highlands; C, Cobequid Highlands; AH, Antigonish Highlands; CBI, Cape Breton Island.

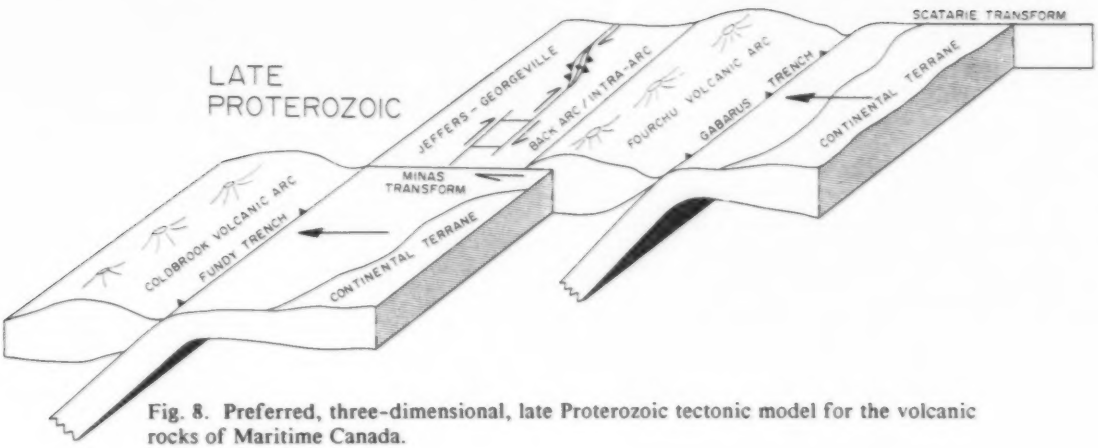

Fig. 8. Preferred, three-dimensional, late Proterozoic tectonic model for the volcanic rocks of Maritime Canada.

Fundy segment, the anomaly lies under the southern margin of the Cobequid/Antigonish highlands and the Caledonian Highlands, respectively. This suggests that the mafic/ultramafic bodies dip steeply north or northeast in these segments. The Collector Anomaly may be imaged by the near vertical zone of strong reflectors recorded on line 86-5B around shot point 2000 between 2.5 and 6 s two-way travel time [Marillier et al., 1989].

Model 1 is not supported by the geophysical data because the spur of the Collector Anomaly along Chignecto Bay is of limited extent. This could be explained away if the boundary was a cryptic suture and all ophiolitic remnants were destroyed. However, the generally mild nature of the late Proterozoic deformation and metamorphism argues against the existence of a cryptic suture.

Model 2 would require a discontinuity in the Collector Anomaly along the Minas Fault, unless Paleozoic movements bent them along the fault. However, in this case one would expect the Collector Anomaly to be squeezed out in the middle of the Minas Fault, when, in fact, the anomaly is wide and continuous through this area.

The Collector Anomaly occupies the position predicted by model 3. The anomaly may be divided into NE and east trending portions that would be related to the trench and the transform fault segments, respectively. The presence of both segments suggests that incomplete suturing led to the preservation of ophiolitic fragments along the late Proterozoic plate boundary. That the Collector Anomaly marks the junction between two Precambrian terranes (Figure 8) that were amalgamated by latest Proterozoic times is indicated by the presence of a lower Paleozoic overstep sequence typical of the Avalon Terrane on both sides of the anomaly where the anomaly intersects the coast near Boston [Keppie, 1989]. The gap in the Collector Anomaly in the Bay of Fundy could be due to the presence of thick Mesozoic sediments in a half graben that neutralizes the geophysical anomalies.

Lefort [1989] related the Collector Anomaly to the Meguma-Avalon boundary; however, while it approximately coincides with this boundary through Nova Scotia, it diverges east of Cape Breton Island and in the Gulf of Maine (Figure 1). East of Nova Scotia, the northern boundary of the Meguma Terrane trends E-W, while the Gabarus segment of the Collector Anomaly diverges northeastwards before turning eastwards along the Scatarie segment. In the Gulf of Maine the northern edge of the Meguma Terrane has been drawn at the northern border fault of the Franklin rift [Hutchinson et al., 1988] or at the Nauset Fault [Lefort, 1989], neither of which lies close to the Fundy segment of the Collector Anomaly along the northern side of the Gulf of Maine (Figure 1). On the contrary, in southern New England, the Collector Anomaly lies within the northern part of the Avalon Terrane. Furthermore, Lefort [1989] related the Collector Anomaly to Siluro-Devonian volcanic rocks in the Coastal volcanic belt and its continuation through the Cobequid and Antigonish highlands. However, the composition of these Siluro-Devonian volcanic rocks indicates that they are bimodal, continental rift tholeiitic basalts and felsic volcanic rocks, not ophiolites [Keppie and Dostal, 1980; Gates and Moench, 1981; Murphy, 1987].

CONCLUSIONS

The available data suggest that the late Proterozoic (circa 570-680 Ma) volcanic rocks of southern Cape Breton Island, Antigonish, Cobequid, and Caledonian highlands formed in a convergent plate tectonic setting in which one trench was offset by a transform fault located close to the Minas Fault (Figure 8). The location of this suture is marked by the superimposed positive gravity and magnetic Collector Anomaly inferred to represent late Proterozoic ophiolitic remnants.

The approximate coincidence of the Minas Fault and the Collector suture suggests that the late Proterozoic transform fault controlled the location of the late Paleozoic Minas Fault. Overthrusting of the

Meguma Terrane over the Avalon Terrane was limited on the north by a lateral ramp whose location was determined by a preexisting, late Proterozoic, transform fault. Devono-Carboniferous dextral movements along NE trending faults in southern New Brunswick produced only minor modification to this regional late Proterozoic tectonic pattern.

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